Practical Short Synthesis of 1β-Methylcarbapenem Utilizing a New Dehydration Type Ti-Dieckmann Condensation

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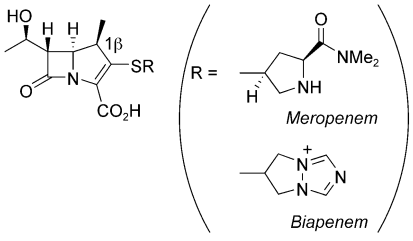
Abstract: An efficient, practical, and stereocontrolled synthesis of 1β-methylcarbapenems has been performed utilizing a new dehydration type of Ti-Dieckmann (intramolecular Ti-Claisen) condensation. This cyclization reaction has the advantage of direct incorporation of the thiol moiety into the target 1β-methylcarbapenem, compared with the traditional basic Dieckmann condensation. Another advantage is the use of environmentally benign (low toxicity and safe) reagents ($TiCl_4$ and Et_3N *or* Bu_3N).

Keywords: cyclization; Dieckmann condensation; 1β-methylcarbapenem; titanium; Ti-Claisen condensation

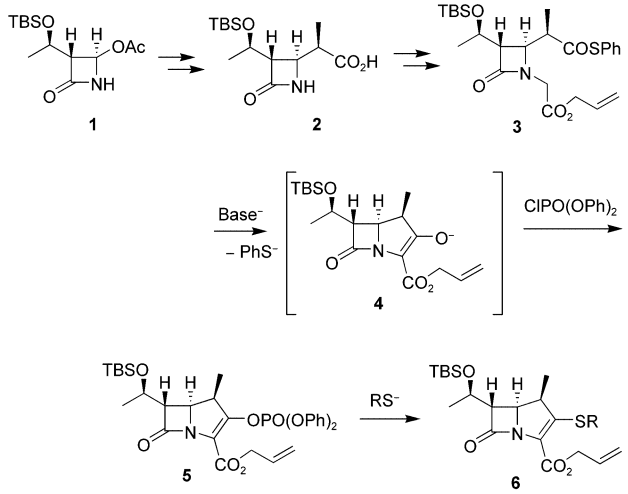
The discovery of 1β-methylcarbapenem (e.g., meropenem[1] and biapenem[2]), which has potent and broad antibacterial activity as well as enhanced metabolic and chemical stability, has prompted many synthetic organic chemists to develop efficient methods for the stereoselective synthesis of the key carbapenem skeleton (Scheme 1). Recent reviews describe the impressive progress in this area.[3]

Among many synthetic methods, 1β-methylcarboxylic acid **2** with four contiguous stereogenic centers is regarded as the most advantageous intermediate, which was synthesized from commercially available 1-acetoxy-2-azetidinone **1** by coupling with propionic acid derivatives (Scheme 2). Some effective methods for stereoselective synthesis of the key 1β-methyl synthon **2** have been developed, however there remains a strong need for practical methods for the subsequent construction of bicyclic framework of 1β-methylcarbapenem **6**. Basic Dieckmann condensation,[4] Rh-carbene insertion,[5] and intramolecular Wittig-type reaction,[6] are representative methodologies.[7] Among them the Dieckmann condensation protocol seems to be the most efficient to date for the practical synthesis of a series of 1β-methylcarbapenems. This method involves three reaction sequences; cyclization of **3** to give **4**, successive formation of enolphosphate **5**, and final substitution with thiolate to give **6** (Scheme 2).

The Ti- and Zr-Claisen and Dieckmann condensations exhibit powerful reactivity and are able to realize C–C bond formations between various carboxylic esters under mild reaction conditions.[8] These characteristic features would be ideal for application of the reaction



Scheme 1. 1β-Methylcarbapenem.



Scheme 2. Synthetic route to 1β-methylcarbapenem **6** utilizing basic Dieckmann condensation.

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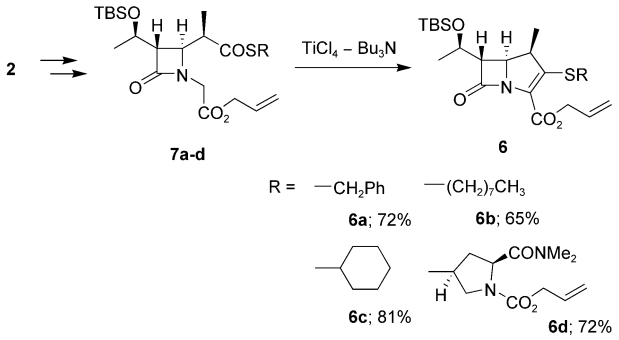
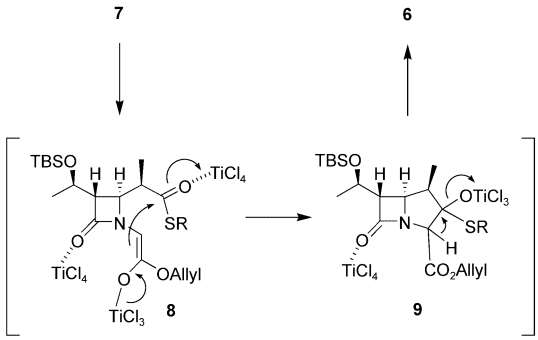


Scheme 3. Dehydration type Ti-Dieckmann condensation of thioester **7a – d**.



Scheme 4. Proposed mechanism of the dehydration type Ti-Dieckmann condensation.

for the construction of the 1β-methylcarbapenem skeleton. We present a short and efficient cyclization reaction between the α-position of allyl esters and carbonyl position of thioesters in **7a – d**, which did not yield basic reagent mediated Dieckmann-products **4** with the elimination of thiols, but yielded vinyl sulfides **6a – d** through a novel dehydration type Ti-Dieckmann condensation (Scheme 3).

Scheme 3 lists four successful results, including the precursor of meropenem, which is one of the most representative 1β-methylcarbapenem antibiotics. Precursor **6d** could be transformed into meropenem by the known method, which involves desilylation followed by Pd-catalyzed deprotection of the allyl moiety in the ester.[1] Optimization of the conditions revealed that 3.0 equiv. of $TiCl_4$ and 3.3 equiv. of Bu_3N were required. When 1.0 equiv. of $TiCl_4$ was used, the desired carbapenem **6** resulted in low yield ($\sim$ 20%). It should be noted that no epimerization of the 1β-position was observed; that is, the four contiguous stereogenic centers were successfully retained, although the 1α-diastereomer of enolate **4** was more thermodynamically stable than the 1β one. In addition, the elimination of dummy benzenethiol and diphenyl chlorophosphate is more atom-economical.

As a proposed mechanism, this unexpected reaction comprises the following steps (Scheme 4); (i) regioselective formation of titanium allyl ester enolates intermediate **8**, (ii) cyclization to form the Ti-intermediate **9** with an sp^3 tetrahedral carbon adjacent to a chiral methyl group, and (iii) elimination of $Ti(=O)Cl_2$ and HCl (net process is dehydration of **7**) to give the desired vinyl sulfides **6**. In general, the thiol function of thioesters is regarded as a more easily displaced moiety, however this unusual behavior is considered to be due to the greater affinity of $TiCl_4$ toward oxygen than that of sulfur. Mukaiyama and his coworkers reported a related condensation reaction in which ketones were transformed into vinyl sulfides with thiols using $TiCl_4$ and Et_3N.[9]

The present straightforward method is more convenient than the basic Dieckmann method and provides a new methodology for the synthesis of 1β-methylcarbapenems.

Experimental Section

(3*S*,4*S*)-1-(Allyloxycarbonylmethyl)-3-[(1*R*)-1-(*tert*-butyldimethylsilyloxy)ethyl]-4-[(1*R*)-1-benzylthiocarbonylethyl]-2-azetidinone (7a)[4c]

To a stirred solution of (3*S*,4*S*)-1-(allyloxycarbonylmethyl)-3-[(1*R*)-1-(*tert*-butyldimethylsilyloxy)ethyl]-4-[(1*R*)-1-carboxyethyl]-2-azetidinone[4c] (200 mg, 0.5 mmol) in benzene (4.0 ml) was added *N*,*N*′-dicyclohexylcarbodiimide (206 mg, 1.0 mmol) and 4-dimethylaminopyridine (12 mg, 0.1 mmol) at 20 – 25 °C under an Ar atmosphere, and the mixture was stirred for 30 min at that temperature. Benzyl mercaptan (248 mg, 2.0 mmol) was added to that mixture, followed by being stirred for 12 h. After Celite filtration, the mixture was concentrated to give the crude product, which was purified by silica-gel column chromatography (hexane : EtOAc = 5 : 1) to give the desired product **3a** as a pale yellow oil; yield: 335 mg (66%). Spectroscopic data matched with the literature.

(3*S*,4*S*)-1-(Allyloxycarbonylmethyl)-3-[(1*R*)-1-(*tert*-butyldimethylsilyloxy)ethyl]-4-[(1*R*)-1-octylthiocarbonylethyl]-2-azetidinone (7b)

A similar procedure as for the preparation of **7a** using octanethiol in the place of benzyl mercaptan; yield: 98%; colorless oil; $[\alpha]_D^{23}$: −31.8 (*c* 0.32, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.079 (3H, s), 0.084 (3H, s), 0.87 (9H, s), 1.21 – 1.37 (17H, m), 1.51 – 1.58 (2H, m), 2.85 (2H, t, *J* = 7.4 Hz), 2.99 – 3.05 (2H, m), 3.90 (1H, d, *J* = 18.0 Hz), 4.07 (1H, dd, *J* = 2.8 and 2.8 Hz), 4.13 – 4.19 (1H, m), 4.25 (1H, d, *J* = 18.0 Hz), 4.62 – 4.64 (2H, m), 5.24 – 5.37 (2H, m), 5.86 – 5.96 (1H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = −4.86, −4.40, 12.24, 13.94, 17.74, 22.48, 22.55, 25.68, 28.66, 28.90, 28.94, 28.99, 29.25, 31.64, 42.50, 49.46, 57.33, 61.08, 65.67, 66.47, 118.68, 131.48, 167.84, 167.88, 201.45; IR (neat): ν = 1770, 1684, 1460, 1412, 1375 cm^{-1}; HRMS (FAB): calcd. for $C_{27}H_{49}NO_5SSi$ (M^+): 527.3101; found ($M^+ + 1$): 528.3218.

(3*S*,4*S*)-1-(Allyloxycarbonylmethyl)-3-[(1*R*)-1-(*tert*-butyldimethylsilyloxy)ethyl]-4-[(1*R*)-1-cyclohexylthiocarbonylethyl]-2-azetidinone (7c)

A similar procedure as for the preparation of **7a** using cyclohexanethiol in the place of benzyl mercaptan; yield: 82%; pale yellow oil; $[\alpha]_D^{23}$: −33.9 (*c* 0.23, $CHCl_3$). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.082 (3H, s), 0.085 (3H, s), 0.88 (9H, s), 1.20–1.48 (11H, m), 1.53–1.76 (3H, m), 1.81–1.94 (2H, m), 2.95–3.02 (2H, m), 3.40–3.54 (1H, m), 3.90 (1H, d, *J* = 18.0 Hz), 4.07 (1H, dd, *J* = 2.8 and 2.8 Hz), 4.12–4.19 (1H, m), 4.26 (1H, d, *J* = 18.0 Hz), 4.62–4.64 (2H, m), 5.24–5.37 (2H, m), 5.86–5.96 (1H, m); ^{13}C NMR (75 MHz, $CDCl_3$): δ = −4.85, −4.41, 12.14, 17.76, 22.58, 25.35, 25.70, 32.64, 32.81, 42.43, 42.48, 49.37, 57.38, 61.01, 65.68, 66.50, 118.70, 131.47, 167.84, 167.92, 201.21; IR (neat): ν = 1766, 1680, 1450, 1412, 1375 cm^{-1}; HRMS (FAB): calcd. for $C_{25}H_{43}NO_5SSi$ (M^+): 498.2710; found ($M^+ + 1$): 498.2689.

(3*S*,4*S*)-1-(Allyloxycarbonylmethyl)-3-[(1*R*)-1-(*tert*-butyldimethylsilyloxy)ethyl]-4-{(1*R*)-1-[(3*S*,5*S*)-1-allyloxycarbonyl-5-dimethylaminocarbonylpyrrolidin-3-yl]thiocarbonylethyl}-2-azetidinone (7d)[4c]

To a stirred solution of [(3*S*,5*S*)-1-allyloxycarabonyl-3-benzoylthio-5-dimethylaminocarbonylpyrrolidine (435 mg, 1.2 mmol) in CH_3CN (2.0 mL), $NaOCH_3$ (28% in CH_3OH, 243 mg, 1.26 mmol) was added at −15 to −10 °C under an Ar atmosphere, and the mixture was stirred for 1 h at that temperature. To the mixture, phosphoric acid (85%, 145 mg, 1.26 mmol) was added, and then dried (Na_2SO_4). After Celite filtration the mixture was concentrated to a volume of *ca.* 2 mL, which contained (3*S*,5*S*)-1-allyloxycarbonyl-5-dimethylaminocarbonyl-3-mercaptopyrrolidine.

N,*N*′-Carbonyldiimidazole (195 mg, 1.20 mmol) was added to a stirred solution of (3*S*,4*S*)-1-(allyloxycarbonylmethyl)-3-[(1*R*)-1-(*tert*-butyldimethylsilyloxy)ethyl]-4-[(1*R*)-1-carboxyethyl]-2-azetidinone[4c] (400 mg, 1.0 mmol) in CH_3CN (8.0 ml) at 20–25 °C under an Ar atmosphere, and the mixture was stirred for 1 h at that temperature. To the mixture, a solution of (3*S*,5*S*)-1-allyloxycarbonyl-5-dimethylaminocarbonyl-3-mercaptopyrrolidine in CH_3CN (*ca.* 2.0 mL) prepared above and Et_3N (121 mg, 1.20 mmol) in CH_3CN (1.5 mL) were successively added, followed by stirring for 6 h. 1 M aqueous HCl solution was added to the mixture, which was extracted by EtOAc. The organic phase was washed with water, brine, dried (Na_2SO_4), and concentrated. The obtained crude product was purified by silica gel column chromatography (hexane:EtOAc = 1:2) to give the desired product **7d** as a colorless oil; yield: 515 mg (80%). Spectroscopic data matched with the literature.

Allyl (4*R*,5*S*,6*S*)-3-Benzylthio-6-[(1*R*)-1-(*tert*-butyldimethylsilyloxy)ethyl]-4-methyl-7-oxo-1-azabicyclo[3.2.0]hept-2-ene-2-carboxylate (6a)[4c]

$TiCl_4$ (1.0 M solution in CH_2Cl_2; 0.60 mL) was added to a stirred solution of **7a** (101 mg, 0.2 mmol) and Bu_3N (122 mg, 0.66 mmol) in CH_2Cl_2 (0.5 mL) at −45 to −40 °C under an Ar atmosphere, and the mixture was stirred for 1 h. Water was added to the mixture, which was extracted with ether. The organic phase was washed with water, brine, dried (Na_2SO_4), and concentrated. The obtained crude product was purified by silica gel column chromatography (hexane:EtOAc = 40:1) to give the desired product 6a as a pale yellow oil; yield: 71 mg (72%). Spectroscopic data matched with the literature.

Allyl (4*R*,5*S*,6*S*)-6-[(1*R*)-1-(*tert*-Butyldimethylsilyloxy)ethyl]-4-methyl-3-octylthio-7-oxo-1-azabicyclo[3.2.0]hept-2-ene-2-carboxylate (6b)

A similar procedure as for the preparation of **6a** using **7b** in the place of **7a**; yield: 65%; pale yellow oil; $[\alpha]_D^{23}$: +54.0 (*c* 0.13, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.079 (6H, s), 0.88 (9H, s), 1.22–1.46 (19H, m), 1.61–1.68 (2H, m), 2.75–2.88 (2H, m), 3.18 (1H, dd, *J* = 6.6 and 2.4 Hz), 3.25–3.33 (1H, m), 4.12–4.14 (1H, dd, *J* = 9.2 and 2.6 Hz), 4.19–4.26 (1H, m), 4.66–4.81 (2H, m), 5.21–5.25 (1H, m), 5.42–5.47 (1H, m), 5.90–6.00 (1H, m); ^{13}C NMR (75 MHz, $CDCl_3$): δ = −5.02, −4.28, 13.97, 16.82, 17.85, 22.52, 25.62, 28.68, 29.00, 29.59, 31.49, 31.66, 42.92, 55.98, 59.96, 65.33, 66.31, 117.95, 123.98, 131.68, 151.15, 160.71, 172.49; IR (neat): ν = 1718, 1655, 1462, 1379 cm^{-1}; HRMS (FAB): calcd. for $C_{27}H_{47}NO_5SSi$ (M^+): 509.2995; found ($M^+ + 1$): 510.2889.

Allyl (4*R*,5*S*,6*S*)-6-[(1*R*)-1-(*tert*-Butyldimethylsilyloxy)ethyl]-3-cyclohexylthio-4-methyl-7-oxo-1-azabicyclo[3.2.0]hept-2-ene-2-carboxylate (6c)

A similar procedure as for the preparation of **6a** using **7c** in the place of **7a**; yield: 81%; pale yellow oil; $[\alpha]_D^{23}$: +85.0 (*c* 0.15, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.082 (3H, s), 0.087 (3H, s), 0,88 (9H, s), 1.19–1.52 (11H, m), 1.59–1.71 (1H, m), 1.76–1.86 (2H, m), 1.91–2.02 (2H, m), 3.03–3.11 (1H, m), 3.19 (1H, dd, *J* = 5.6 and 2.8 Hz), 3.24–3.32 (1H, m), 4.15 (1H, dd, *J* = 9.6 and 2.4 Hz), 4.21–4.27 (1H, m), 4.65–4.82 (2H, m), 5.21–5.25 (1H, m), 5.42–5.47 (1H, m), 5.91–6.00 (1H, m); ^{13}C NMR (75 MHz, $CDCl_3$): δ = −5.02, −4.32, 17.15, 17.89, 22.39, 25.33, 25.64, 26.04, 32.08, 35.94, 43.11, 43.84, 55.64, 60.11, 65.33, 65.98, 117.93, 125.11, 131.70, 149.39, 160.58, 172.66; IR (neat): ν = 1718, 1464, 1450, 1381 cm^{-1}; HRMS (FAB): calcd for $C_{25}H_{41}NO_5SSi$ (M^+): 527.2526; found ($M^+ + 1$): 528.2478.

Allyl (4*R*,5*S*,6*S*)-3-[1-Allyloxycarbonylpyrrolidin-(3*S*,5*S*)-5-dimethylaminocarbonyl-3-ylthio]-6-[(1*R*)-1-(*tert*-butyldimethylsilyloxy)ethyl]-4-methyl-7-oxo-1-azabicyclo[3.2.0]hept-2-ene-2-carboxylate (6d)[4c]

A similar procedure as for the preparation of **6a** using **7d** in the place of **7a**; yield: 72%; pale yellow oil. Spectroscopic data matched with the literature.

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